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Added Value of Reliability to a Microgrid: Simulations of Three California Buildings

Chris Marnay, *Member, IEEE*, Judy Lai, Michael Stadler, and Afzal Siddiqui

Abstract—The Distributed Energy Resources Customer Adoption Model is used to estimate the value an Oakland nursing home, a Riverside high school, and a Sunnyvale data center would need to put on higher electricity service reliability for them to adopt a Consortium for Electric Reliability Technology Solutions Microgrid (CM) based on economics alone. A fraction of each building's load is deemed critical based on its mission, and the added cost of CM capability to meet it added to on-site generation options. The three sites are analyzed with various resources available as microgrid components. Results show that the value placed on higher reliability often does not have to be significant for CM to appear attractive, about 25 \$/kW•a and up, but the carbon footprint consequences are mixed because storage is often used to shift cheaper off-peak electricity to use during afternoon hours in competition with the solar sources.

Index Terms—buildings, cogeneration, cooling, dispersed storage and generation, microgrids, optimization methods, power quality, power system reliability, power system economics.

I. INTRODUCTION

In prior research, many authors have described the emerging technologies arising from the power electronics that accompany many distributed energy resources (DER) such as DC power sources, e.g. photovoltaic (PV) systems and battery storage, asynchronous generators such as microturbines, and variable speed engine generator sets (gensets) [1,2,3]. Together with high-speed switches that permit seamless grid disconnect and reconnect, these power electronic devices will enable formation of *microgrids* that operate semiautonomously from the traditional centralized power system, or *macrogrid*. This paper specifically focuses

on the Consortium for Electric Reliability Technology Solutions (CERTS) Microgrid (CM) based on multiple nameplate 100 kW Tecogen Premium Power Modules (CM-100) engine generators (gensets). A second microgrid concept in vogue explores the possibility that segments of the macrogrid might function independently, or islanded, under certain conditions for limited periods. This second type of microgrid is not covered in this paper, which rather focuses on building or multi-building scale CMs that might be considered equivalent to current medium and large commercial utility customers. Such microgrids are a local clusters of sources and sinks that operate semi-autonomously of the macrogrid, able to island and reconnect as circumstances dictate, and able to provide power quality and reliability (PQR) different from general macrogrid standards. Many microgrid demonstrations are under way in North America, Europe, and Japan, while several other countries have research programs starting up, notably Singapore, Australia, Korea, and China.

Two key advantages of microgrids are that: 1. thermal generation close to loads facilitates the application of small-scale combined heat and power (CHP) with potentially significant cost and carbon emissions benefits; and 2. a more favorable environment can be potentially created for harvesting and integration of diffuse local renewable sources. A significant third potential benefit to date much less quantitatively explored is that microgrids can also locally control the PQR delivered to loads. This concept has two levels. The first is that since by definition a microgrid is able to function islanded from the macrogrid, higher reliability can be achieved for all its loads. The second is that *heterogeneous PQR* (HeQ) might be provided to various enduses in keeping with their highly diverse PQR requirements [4,5]. In this paper only a hybrid of these two reliability levels is considered. A certain share of building load is designated *sensitive* and the on-site CM assets must be likely to meet these loads in the event of lost macrogrid power. Further, note that only reliability in the sense of power availability is addressed here. Other aspects of PQR, such as voltage stability, harmonics, etc., might also be controlled within microgrids, but they are not considered in this paper [6].

Estimation of the value of improved reliability has been pursued via analysis of the attractiveness of a CM. Optimal microgrids are found with this engine together with other microgrid resources available as equipment choices. By

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comparing true minimum cost solutions with ones in which the CERTS Microgrid technology is chosen shows how much the site would have to value the reliability benefit for it to adopt the CM. In other words, this approach attempts to find the cost gap that need to be made up for a CM to be adopted.

II. MICROGRIDS AND PQR

In developed economies worldwide, the current power delivery paradigm has been in place worldwide for a long time, i.e. since the emergence of polyphase AC systems around the turn of the last century. In outline, this dominant paradigm consists of large-scale central station generation, long distance bulk transmission of energy over centrally operated high voltage meshed grids, and local distribution at ever lower voltages through simpler partially locally managed, unidirectional, radial lines. A key feature of this structure is that, in principle, universal service is delivered at a consistent level of PQR throughout large regions. For example, PQR targets are consistent virtually all across North America, and where standards cannot be met, it is usually the result of a local technical difficulty and not the outcome of a deliberate attempt to deviate from the universal norm. This predictability of service delivers an enormous economic benefit because all types of electrical equipment can be built to match the homogeneous universal standard. Indeed, this traditional *homogeneous PQR* (HoQ) paradigm has served developed economies well for a very long period during which the uses for and consumption of electricity have increased enormously, even at times explosively. As is often observed, modern life as we currently experience it seems impossible without such ubiquitous, universal, reliable, high-quality power.

To be clear, higher PQR is unequivocally better than lower, i.e. it is an economic *good*; the current dilemma springs from the technical challenge and cost of improving PQR, not from any doubt about its desirability. Changes in expectations for the power supply system on both the supply and demand sides are bringing us to a turning point in its evolution and quite possibly to the first paradigm shift in over a century. Improving traditional universal service to the point at which it can meet the requirements of sensitive or modern digital loads may be unnecessarily costly. The changes on the demand-side result from our seemingly unquenchable thirst for electricity in an emerging digital age that is significantly tightening our PQR requirements for some applications, while on the supply-side, increased penetration of intermittent resources, concerns about terrorism, restrictions on system expansion, and the uncertainties of volatile markets in energy-short times bring our ability to maintain current PQR standards into doubt.

In an alternative vision of shown in Fig. 1, PQR diverges from standard HoQ downstream of the substation. The x-axis shows development of the power system over its history, while the y-axis shows reliability in nines of availability together with the equivalent annual expected outage time.

Initially, power supply was localized and equipment was unreliable so delivered PQR was poor overall. Over the

industry's history, systems were interconnected over large regions and improved equipment, procedures, and training slowing improved the entire system. In recent years though, improvements have become slow or non-existent. Looking forward, in the HeQ view of future development of power provision, safe and economic operation of the high voltage meshed grid relies as it always has on tight standards and centralized operation; however, downstream, PQR becomes increasingly heterogeneous, with delivered electricity to the end-use potentially diverging considerably. As seen in Fig. 1, following the northeast U.S. blackouts of the 1970s, dispersed resources emerged with a larger role as requirements for local back-up were implemented. In this paradigm, heterogeneity increases downstream, with localized systems able to island and continue service when the macrogrid cannot. These localized microgrids can be of either of the two types described in section I, i.e. either smart distribution segments or independent systems on the customer side of the meter.

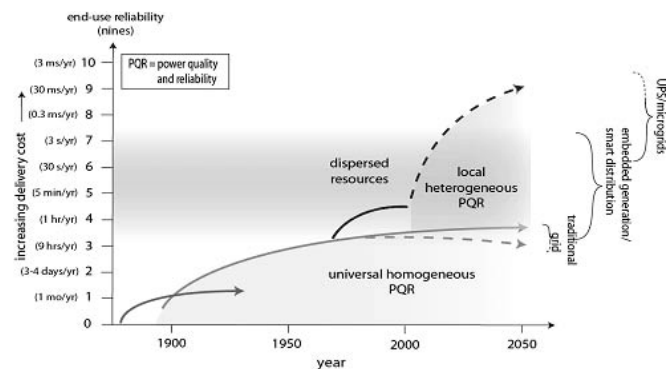


Fig. 1. Provision of local heterogeneous PQR

Please note that in stark contrast to the HoQ paradigm, the PQR of actual enduse loads are highly heterogeneous, as shown in Fig. 2.

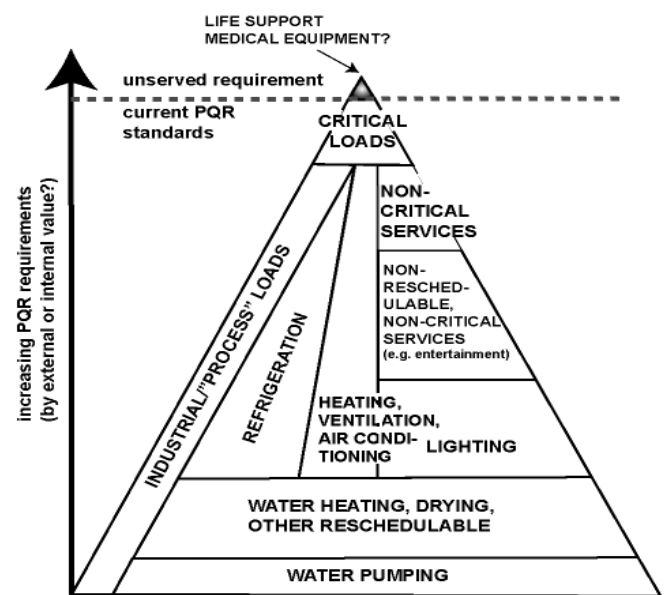


Fig. 2. Heterogeneity of enduse PQR requirements

This pyramid demonstrates that enduse loads cover a wide range of PQR requirements. Some common loads, such

as water pumping, are widely agreed to have low PQR requirements and appear at the bottom of the pyramid, and vice-versa. Other loads can be much harder to classify; e.g., refrigeration is reschedulable in many applications, but might be critical in others, such as medication storage. At the top of the pyramid, the exposed peak above current standards shows that not all requirements are currently met. The layout of end-uses shown is highly speculative and simply intended to show how HeQ might be considered. Indeed, there is no clear framework for classifying loads by their PQR requirement, and much less any commensurate data collection efforts. More important is the pyramid shape itself. It is clearly not a natural law that low PQR demanding loads in the base vastly outnumber critical ones near the apex; however, if microgrids behave in an economically rational manner, they would attempt to make them so. In other words, serving the low requirements loads at the bottom is cheap, and vice-versa for the sensitive loads at the top.

Microgrids should be trying, therefore, to classify as much of the overall load in the base as possible. For example, equipment considered a sensitive load, it is often only a small share of the energy that truly is essential, e.g. to run controls, while much of the energy consumed could be of relatively low quality. In such cases, two separate qualities of service might be delivered to the respective parts of the device. Analysis of PQR requirements in a form like the pyramid could potentially lead to the clustering of like PQR loads on certain circuits and the provision of electricity of appropriate quality to that circuit, and the disaggregation of some loads into constituent parts of varying PQR requirements. At the same time, the effective provision of high PQR locally to sensitive loads could potentially lower the societal optimum for grid service, as seen in Fig. 1.

III. DISTRIBUTED ENERGY RESOURCES CUSTOMER ADOPTION MODEL

DER-CAM solves a commercial building's microgrid investment optimization problem given its end-use energy loads, energy tariff structures and fuel prices, and an arbitrary list of equipment investment options. The Sankey diagram in Fig. 3 shows energy flows in a building scale microgrid.

DER-CAM analysis begins with the services requirements shown on the right, electricity only, e.g. computing, cooling, heating, etc. Farther to the right passive measures are shown, i.e. many services can be provided by improving the building envelope, by daylighting, etc., which tend to lower the requirements on active systems shown to the left. DER-CAM aims to solve the Sankey systemically, taking the interactions between end-uses and simultaneity of solutions into account. An example of interactions might be that a window retrofit might change the active heating, cooling, and even lighting loads. Cooling is the classic example of the latter, simultaneity, effect. For example, partially cooling a building using waste heat fired absorption

technology lowers the residual electrical load and permits downsizing of all electrical systems, including on-site generating capacity.

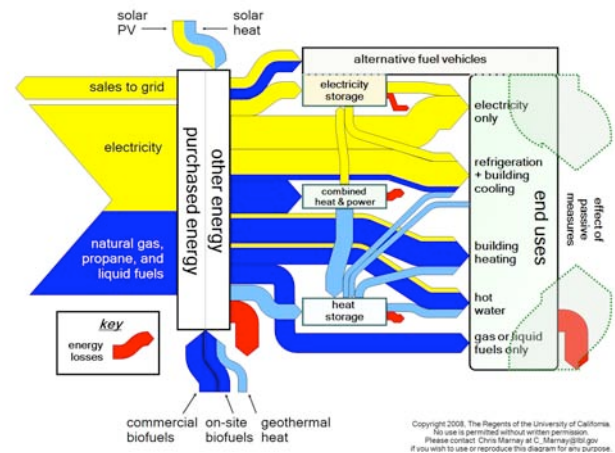


Fig. 3. Energy flows in a building microgrid

The approach is fully technology-neutral and can include energy purchases, on-site conversion, both electrical and thermal on-site renewable harvesting and/or storage, and end-use efficiency investments. Regulatory, engineering, and investment constraints are all considered. Energy costs are calculated using a detailed representation of utility tariff structures and fuel prices as well as amortized DER investment costs and operating and maintenance (O&M) expenditures. For a specific site, the source of end-use energy load estimates is actual data (source of the data center example below), building energy simulation using a model based on the DOE-2 engine, such as eQUEST (source of the nursing home example), or simulation using a more sophisticated model, such as EnergyPlus (source of the Riverside School example) [7].

The output from DER-CAM is a cost-minimizing equipment combination for the microgrid, including CHP equipment and renewable sources. The model chooses the optimal combination, fully taking the simultaneity of choices into account. The results of DER-CAM suggest not only an optimal (potentially mixed technology) microgrid, but also an optimal operating schedule that can serve as the basis for a microgrid control strategy; however, the rigors of optimization necessitate simplification of many real-world engineering constraints that would in practice necessarily be addressed through more detailed engineering analysis and system design.

Optimal combinations of equipment involving PV, thermal generation with heat recovery, thermal heat collection, heat-activated cooling, and both thermal and electrical storage can be identified in a way intractable by simple searching. The economics of storage are particularly complex, both because they require optimization across multiple time steps and because of the influence of tariff structures. This paper reports results of three example California building microgrids in which all these DER-CAM capabilities are applied, and additionally the added value of

the microgrids' reliability is considered.

IV. EXAMPLE BUILDINGS

An earlier market assessment showed that nursing homes, schools, and data centers are three promising markets for the CM, so end-use data sets were collected for representative example buildings of each of these three types in both California and New York. The details are shown in Table 1.

TABLE 1
CHARACTERISTICS OF THE CALIFORNIA TEST BUILDINGS

	floor-space (000m ²)	electricity peak load (MW)	annual electricity use (MWh)	annual NG use (GJ)	F _{s,base}	F _{s,peak}
nrsng. home	32	0.96	5 762	20 542	0.5	0.1
school	18	0.88	1 509	2 626	0.25	0
data center	0.6	1.8	11 421	0	1	1

Data sets for these example buildings were obtained in diverse ways. The nursing home is based on an Oakland example taken from the California Commercial End-Use Survey (CEUS). The school is a standard building model taken from a database of commercial prototype EnergyPlus models. The data center is based on billing information for a real Silicon Valley facility. Fuel price levels and spark spread are typically favorable to on-site generation in California. Both Pacific Gas & Electric, which serves the nursing home and data center, and Southern California Edison, which serves the school, have time-of-use tariffs with stiff demand charges.

The F_{s,base} and F_{s,peak} variables in Table 1 refer to assumptions about the extent to which site loads are considered critical, and Fig. 4 shows how the F_{s,base} and F_{s,peak} fractions are applied to the loads of a specific day.

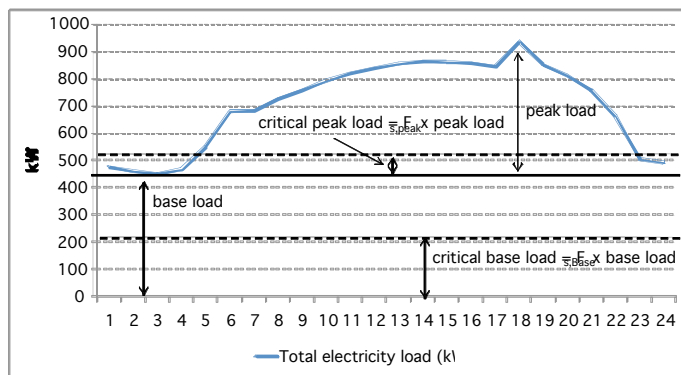


Fig. 4. Calculation of the sensitive load

These two fractions of base and peak loads respectively that must be met during loss of grid power, i.e. the available on-site generation and storage capacity must exceed these ratings. The load fractions considered critical are by assumption only, but within the DER-CAM framework an economic value of the added reliability is sought.

The essence of the CM technology is that smart added to the on-board electronics of some CM devices allows stable

and safe islanded operation without the need for complex supervisory controls. This approach allows plug-and-play development of a microgrid that can potentially provide high and HeQ with a minimum of specialized site-specific engineering. Based on expert opinion, the PQR features are assumed to add \$25/kW to the CM-100 engine installed cost plus \$100/kW is required for the fast switch, which separates from the macrogrid seamlessly during a grid disturbance.

While it may sound as if the cost of an alternative, such as backup generation, is a reasonable indicator of the site's willingness to pay for the higher reliability, in practice this faces three problems. First, some critical loads either require backup by code or are of such high value that cost is no object, i.e. having on-site generation offers limited advantage to such customers. Second, the advantage of a CM is coverage of relatively short disturbances, e.g. ones for which on-site fuel storage would not be required. Third, short outages are difficult to include in DER-CAM's hourly time resolution. The approach taken in this study has two-steps. In the first, the true optimum system is found, and in the second, a system is forced into existence that meets the critical load requirement. Then a value of reliability is incrementally added to the objective function until the equivalent cost of the optimum system is achieved. The value necessary for this equivalency represents the value the site must put on the added reliability for this capability to be cost effective.

V. AVAILABLE TECHNOLOGIES

The DER-CAM runs reported below include multiple available technologies in addition to the ones that appear in the results of the next section, including a phosphoric acid fuel cell, photovoltaics, and flow batteries. In other words, under the cost assumptions used and without consideration of possible subsidies few of the technologies available ever enter minimum cost solutions. Only the characteristics of chosen technologies are reported here in Tables 2 and 3.

TABLE 2
CHARACTERISTICS OF THE CM-100 GENSET

	CM-100
capacity (kW)	100
sprint capacity (kW)	125
installed costs no-CHP (\$/kW)	2400
installed costs with CHP (\$/kW)	3000
variable maintenance (\$/kWh)	0.02
Efficiency (%), (HHV)	26
lifetime (a)	20

As is apparent from Tables 2 and 3, equipment is represented in DER-CAM in two distinct ways, as *discrete* or *continuous* technologies. The model is solved as a mixed integer linear program, meaning that only whole units are legitimate integer variables. Only the CM-100 is of this kind. The other options are represented as continuous technologies meaning that any size of equipment is legitimate. Note that even though any size can appear in the solution, these types of equipment are also subject to scale

economies, and shown by the existence of the intercept terms in Table 3.

TABLE 3
CHARACTERISTICS OF THE CONTINUOUS TECHNOLOGIES

	lead- acid batteries	thermal storage	absorption chiller	solar thermal
intercept (\$)	295	10000	20000	1000
variable costs (\$/kW/\$/kWh)	193	100	127	500
lifetime (a)	5	17	15	15

Since the purpose of this study concerns the role of the added reliability benefit of a CM, the potential of various resources to meet load is a key assumption. Clearly achieving a complete picture of the potential contribution of various assets would be a significant undertaking. Engines are generally reliable and have high availability, but fuel supply may be interrupted. Batteries are extremely reliable sources, but may be at a low state of charge at the time needed. PV is only available in daylight hours, and even then output is contingent on weather conditions. Further, normal loss of load probability calculations would be difficult for microgrids because back-stop grid service already has a 3-4 nines availability, making estimates of probabilities small enough for numerical concerns to arise. For the purposes of this study, a simple availability factor was attached to each resource to reflect the likelihood it would be able to supply loads in the event of a grid disturbance. For the selected technologies, this value was 0.9 for the CM-100 and 0.21 for the lead-acid battery. Even though flow batteries were given a full availability value of 1.0, they are too expensive to be chosen, and PV is undoubtedly disadvantaged by its low value of 0.22.

VI. RESULTS

Each of the three building results tables, 4-6, report three cases. The *do-nothing* case, run 1, represents the solution if the site buys its electricity and NG from its local utility at normal tariffed rates. The *optimal system no CM* case, run 2, is the pure optimal minimum cost system with neither the costs nor the benefits of improved PQR. The *CM system matching 2* case is the result in which the added cost of CM capability has been included and the objective function balanced to find the necessary value of the added benefit to the site. This key result is the *value of CM* result.

A. Nursing Home

To supply the 50% of the base and 10% of the peak load assuming critical during a macrogrid failure, CM capability of 260 kW is necessary. In this case, the CM capabilities do not change the installed equipment selection, i.e. runs 2 and 3 produce the same outcome. This outcome suggests that the found value of CM is exactly equivalent to the extra cost of CM capability for the 260 kW of critical load. Note also,

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that in this case cost savings are noticeable, around 4%, and carbon footprint is noticeably reduced, by about 13%. In this and all results, the carbon emissions of the site include estimated emissions resulting from utility power generation and delivery [8].

TABLE 4
NURSING HOME RESULTS

	run 1	run 2	run 3
do nothing		optimal system no CM	CM system matching 2
chosen equipment			
CM-100 + CHP (kW)		300	300
switch size (kW)		n/a	260
abs. chiller (kW elec.)		48	48
solar thermal (kW)		134	134
electric storage (kWh)		0	0
thermal storage (kWh)		0	0
annual costs (k\$)			
electricity	758	429	429
NG	206	359	359
onsite DG technologies	n/a	138	135
value of CM (\$/kW•a)	n/a	n/a	≤25
Total	964	926	924
% savings	n/a	3.9	4.1
annual energy consumption (GWh)			
electricity	5.8	3.2	3.2
NG	5.7	10.0	10.0
annual carbon emissions (t/a)			
emissions	1088	945	945
% savings	n/a	13.1	13.1

B. School

Note the interesting optimal solution, run 2, in this case. No engines are chosen, but an absorption chiller is installed, largely served by solar thermal collection and some NG burning. To supply 25% of the base load during a macrogrid failure, CM capability of only 10 kW is necessary. However, the CM capabilities of the CM-100 do not overcome its disadvantages and none is installed. The unattractiveness of To satisfy the sensitive load constraint 47 kWh of electrical storage is chosen and this provides the PQR benefits.

TABLE 5
SCHOOL HOME RESULTS

	run 1	run 2	run 3
	do nothing	optimal system no CM	CM system matching 2
chosen equipment			
CM-100 + CHP (kW)	n/a	0	0
switch size (kW)		n/a	9.69
abs. chiller (kW elec.)		139	136
solar thermal (kW)		65	65
electric storage (kWh)		0	47
thermal storage (kWh)		0	0
annual costs (k\$)			
electricity	264	246	242
NG	24	26	26
onsite DG technologies	n/a	7.44	254
value of CM (\$/kW•a)	n/a	n/a	< =25
Total	288	280	280
% savings	n/a	2.87	2.83
annual energy consumption (GWh)			
electricity	1.5	1.5	1.5
NG	0.7	0.8	0.8
annual carbon emissions (t/a)			
emissions	360	358	358
% savings	n/a	0.58	0.52

C. Data Center

The data center yields the unquestionably most spectacular results. The cost minimizing solution, run 2, involves only the installation of an absorption chiller fired with NG, resulting in a tiny cost savings of about 0.5% and an almost identical tiny increase in net carbon footprint. However, the CM case, run 3, results in a remarkable shift, with the site installing fully 16 CM-10 engines and a chiller. This results in a small cost savings and similar increased carbon footprint, at the balancing CM value of 125 \$/kW•a. While this may seem like a large cost, for a facility that is critically dependent on high PQR, it may well not be. Such facilities are these typically have back-up generation as well UPS capabilities to cover the transition to on-site generation. The added security of a CM could well be justified in this case. Note that capacity of the CM-100's plus the electrical offset of the chillers exceeds the peak load of the data center,

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>1.9 MW versus 1.8 MW. DER-CAM is additionally compensating for the unreliability of the engines in this case.

TABLE 6
DATA CENTER HOME RESULTS

	run 1	run 2	run 3
	do nothing	optimal system no CM	CM system matching 2
chosen equipment			
CM-100 + CHP (kW)	n/a	0	1600
switch size (kW)		n/a	1788
abs. chiller (kW elec.)		141	316
solar thermal (kW)		0	0
electric storage (kWh)		0	0
thermal storage (kWh)		0	0
annual costs (k\$)			
electricity	1478	1459	871
NG	1.8	9.7	322
onsite DG technologies	n/a	4.0	249
value of CM (\$/kW•a)	n/a	n/a	<=125
Total	1480	1473	1443
% savings	n/a	0.47	2.50
annual energy consumption (GWh)			
electricity	11.42	11.39	8.44
NG	0.00	0.23	9.14
annual carbon emissions (t/a)			
emissions	1599	1606	1632
% savings	n/a	-0.5	-2.0

VII. CONCLUSION

The major outcome of the CM analysis is that the consideration of critical loads and PQR can make a significant difference to microgrid adoption depending on the previously installed equipment and the strength of need for high PQR. The nursing home is already attractive for DER adoption without CM, and consideration of CM makes little difference to the result. A modest PQR benefit value of 25 \$/kW•a incents adoption of CM capability, but since the installed capacity is so similar the cost and benefit of CM are roughly equivalent in this case. In the school example, adoption only changes slightly due to the small critical load assumed. No CM-100 units are installed, and the only

changes occur in lead-acid battery adoption. The requirement to satisfy 100% of the data center load during a grid failure results in significant CM-100 adoption. The data center adopts 16 units, whereas without PQR consideration it does not install any. The derived monetary PQR benefits range from less than 25 \$/kW•a for the nursing home and school examples to 125 \$/kW•a for the data center.

Valuing the PQR benefits of microgrids poses an analytic challenge. Typically building operators do not have solid methods for evaluating such costs and benefits. The approach demonstrated in this paper, relying on DER-CAM runs that find the value of PQR necessary to balance its costs and still meet the best alternative installation represents a manageable way to explore microgrid options.

VIII. ACKNOWLEDGMENT

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X. BIOGRAPHIES



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